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Understanding Distance Uncertainties Using PDV on Dynamic Experiments

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Disclaimer

Understanding Distance Uncertainties Using PDV on Dynamic Experiments

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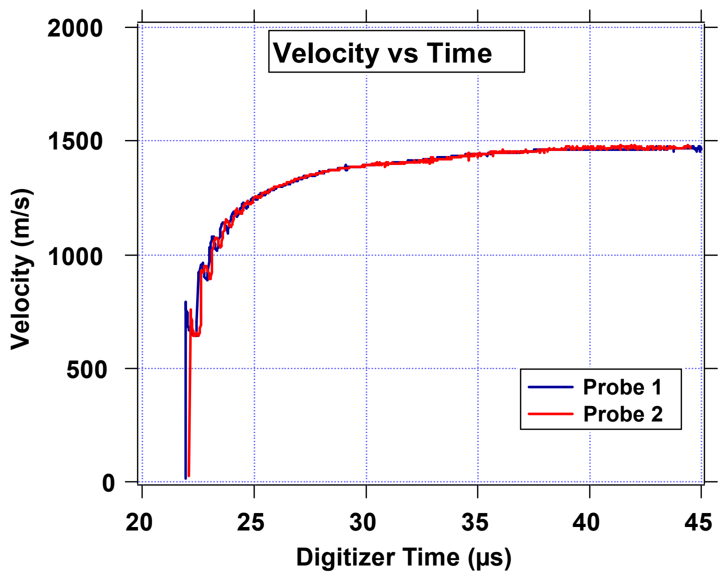
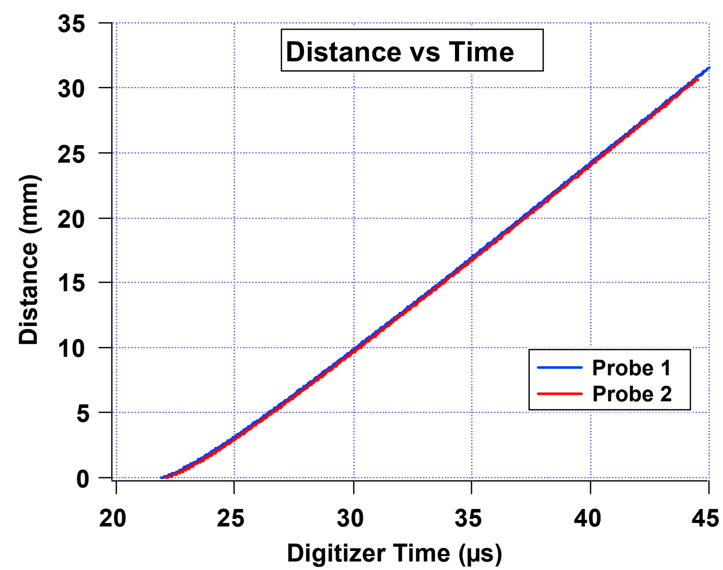
How accurately can we measure distance with PDV on a dynamic experiment?





Integrate the velocity to get the distance:

$$d = \int v dt$$

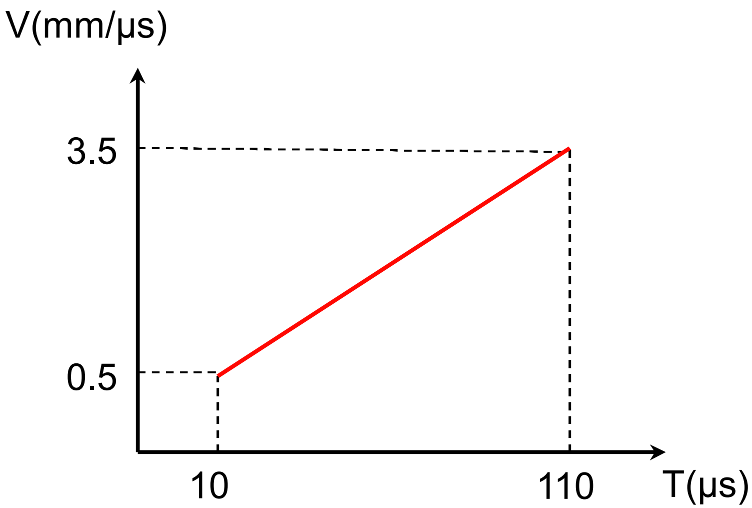
Some designers want the distance uncertainty to be < 10 µm

Uncertainties may accumulate with increasing distance integral.

We will examine the distance uncertainty versus various parameters in the PDV system

	Wavelength				Signal:Noise				Digitizer		FT Window				Phase				Acceleration			
Run#	1550.0	1550.1	1550.2	1550.5	1:0	1:1	1:5	1:10	0 ppm	10 ppm	256	512	1024	2048	0	1/4	1/2	3/4	1	2	3	4
01	X				X				X				X		X					X		
02		X			X				X				X		X					X		
03			X		X				X				X		X					X		
04				X	X				X				X		X					X		
05	X					X			X				X		X					X		
06	X						X		X				X		X					X		
07	X							X	X				X		X					X		
08	X				X					X			X		X					X		
09	X				X				X		X				X					X		
10	X				X				X			X			X					X		
11	X				X				X					X	X					X		
12	X				X				X				X			X				X		
13	X				X				X				X				X			X		
14	X				X				X				X					X		X		
15	X				X				X				X		X				X			
16	X				X				X				X		X						X	
17	X				X				X				X		X							X

Build a velocity profile that corresponds to an interesting range of velocities and times



Calculate the analytic coefficients for velocity and distance

$$v = mt + b$$

$$v = 0.03t + 0.2$$

Area under trapezoid = 1/2 (h1 + h2) * b

A = 0.5 * (0.5 + 3.5) * (100-10)

A = distance = 200 mm

$$d = \frac{1}{2}mt^2 + bt + c$$

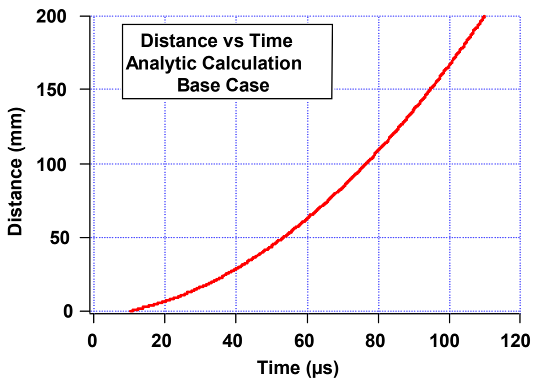
$$d = 0.015t^2 + 0.2t - 3.5$$

Note: 200 mm corresponds to 258065 beat cycles.

Construct the base case beat amplitude from the analytic distance profile

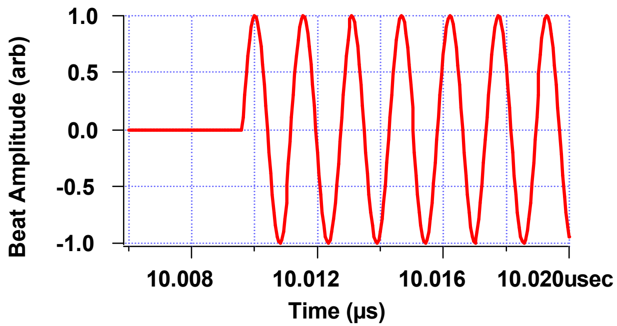
Note: 50 ps/pt = 2.2 Mpts/file

$d = 0.015t^2 + 0.2t - 3.5$



This is my "known" distance profile

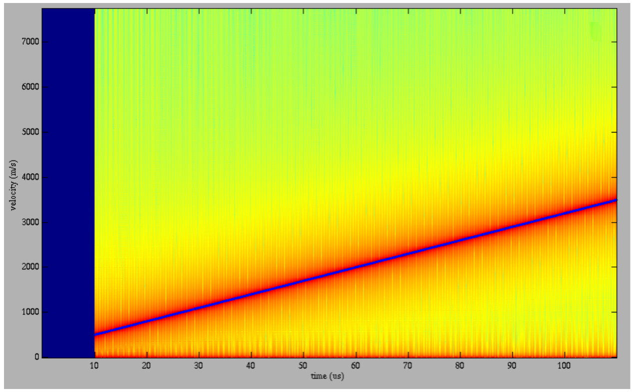
This is my base case beat waveform



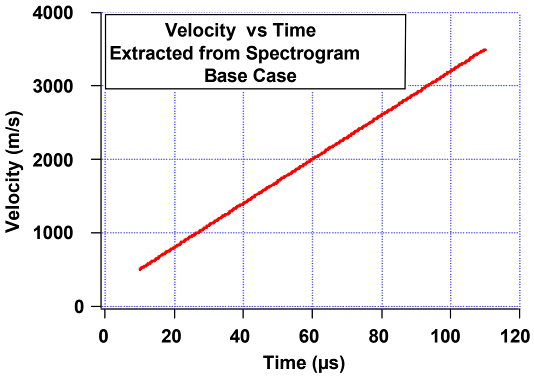
"Base Case" means:
Wavelength = 1550 nm
Noise = 0
Digitizer Sample Time = 50 ps
FT window = 1024 points
Phase = 0
Acceleration = 0.03

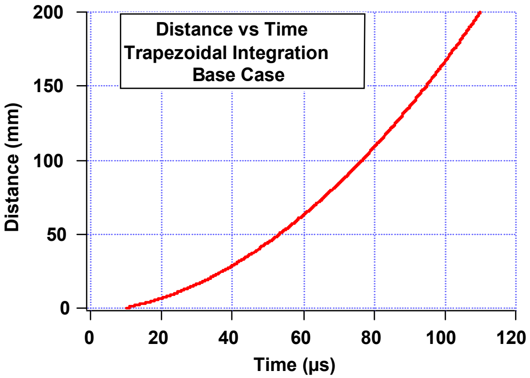
Calculate the spectrograms, extract the velocity profile, integrate to give distance profile

Base case: laser is known = 1550nm, digitizer sample period is known = 50ps, no electrical noise in beat waveform, process spectrogram with 51.2 ns FT windows



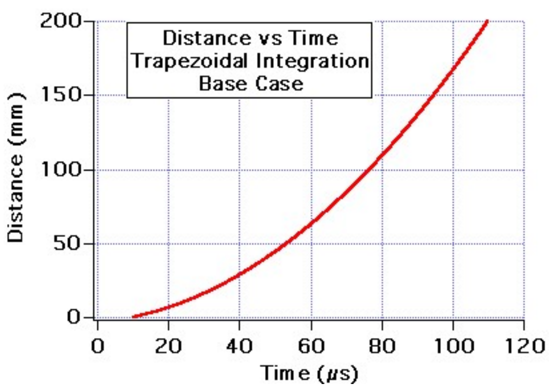
This code is described in "Data Analysis Using the FT Method", Bill Kuhlow, 1st Annual PDV Workshop.



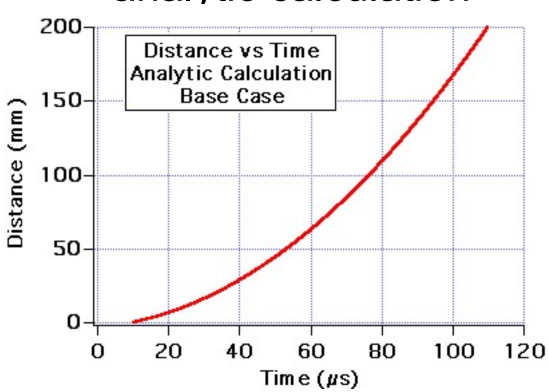


Subtract the trapezoidal integration minus the analytic calculation to get the distance error

trapezoidal integration

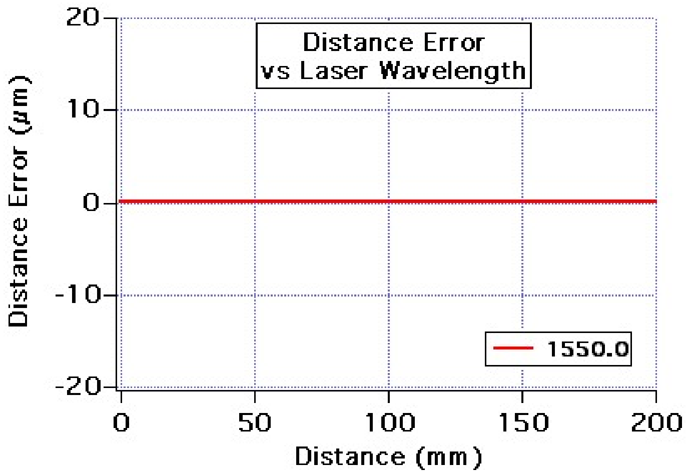


analytic calculation



subtract
to get

Happily, the Base Case
shows very little error.

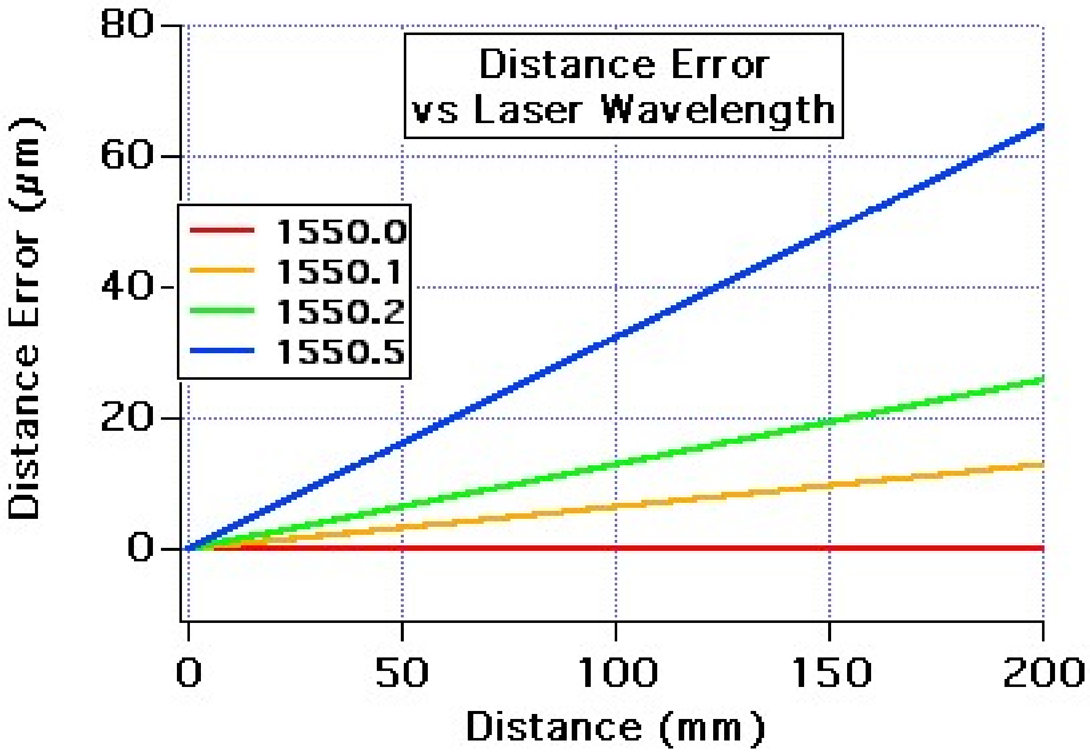


Note: x-axis is distance

Now, let's look at the parameter studies-->

Study the Distance Uncertainty vs Laser Wavelength Uncertainty

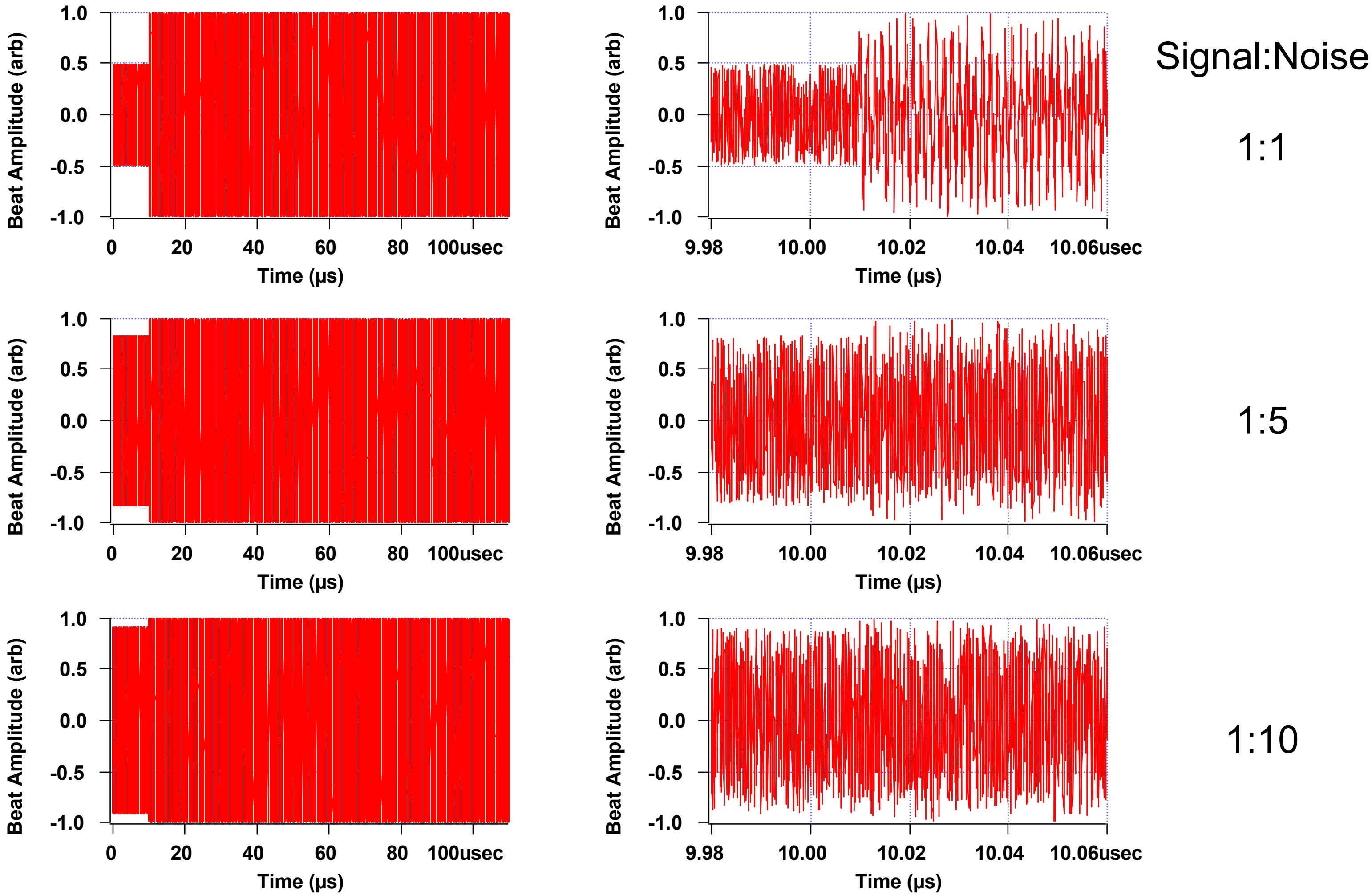
Result: 0.1 nm uncertainty = 17 µm over 200 mm



Our lasers have the following wavelengths:

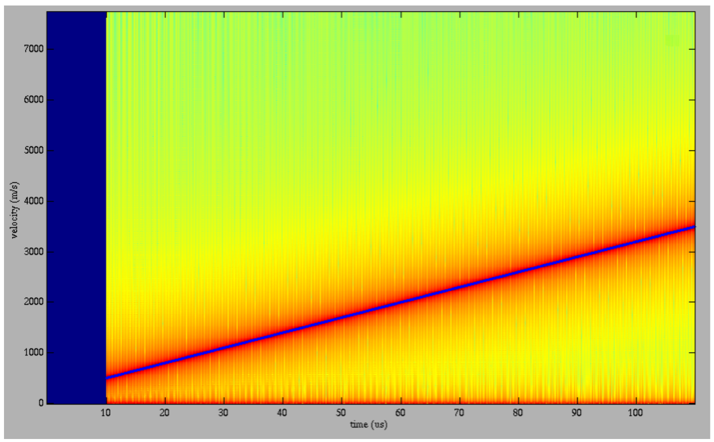
1549.6
1549.8
1550.15
1550.15
1549.88
1550.10

Study the Distance Uncertainty vs Random Noise on the Beat Waveform

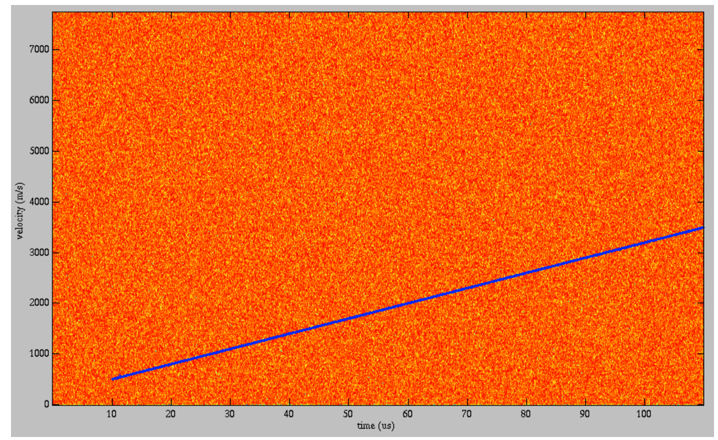


The spectrograms contain more noise with increasing noise on the beat waveforms

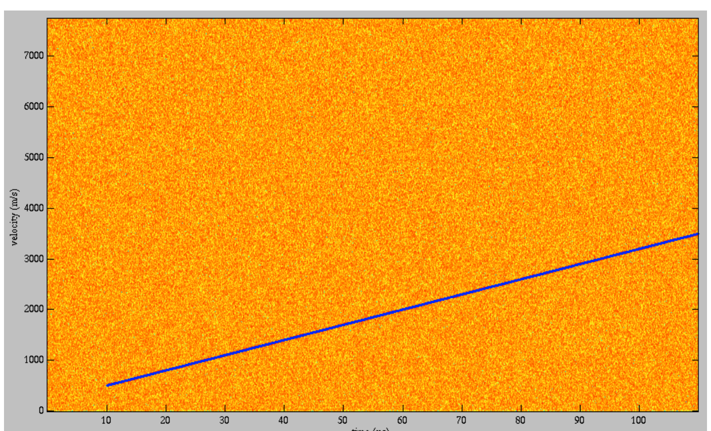
S/N = 1:0



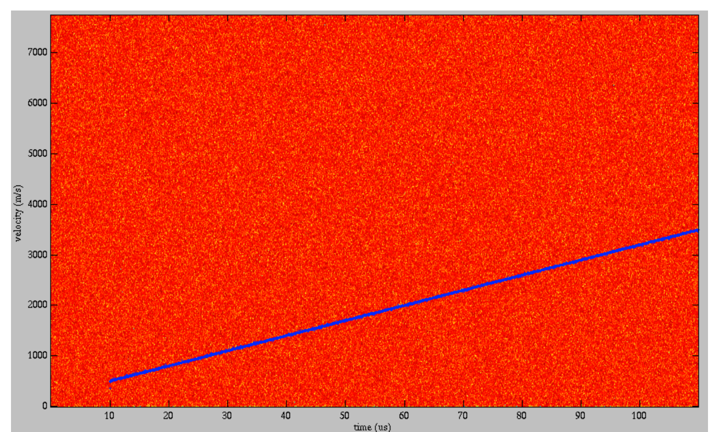
S/N = 1:5



S/N = 1:1

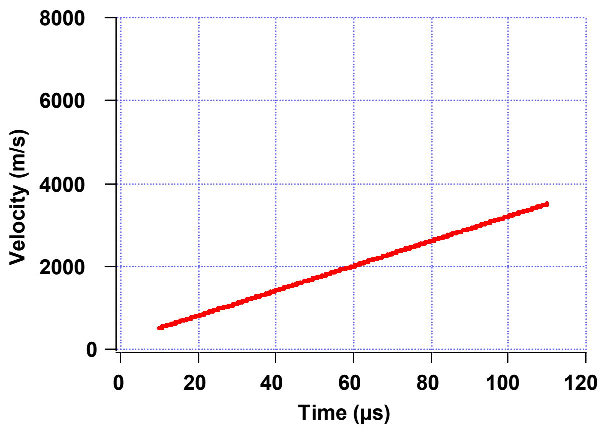


S/N = 1:10

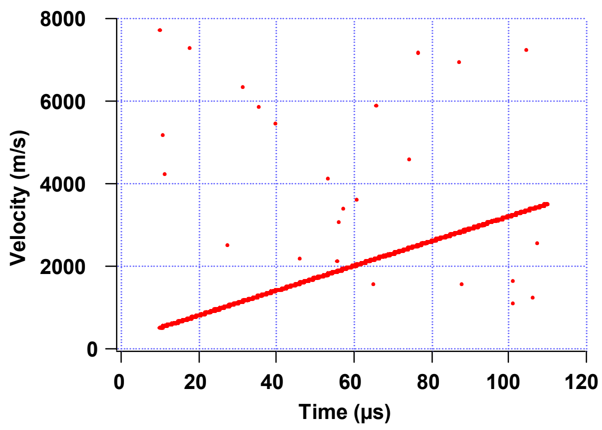


The spectrograms contain more noise with increasing noise on the beat waveforms

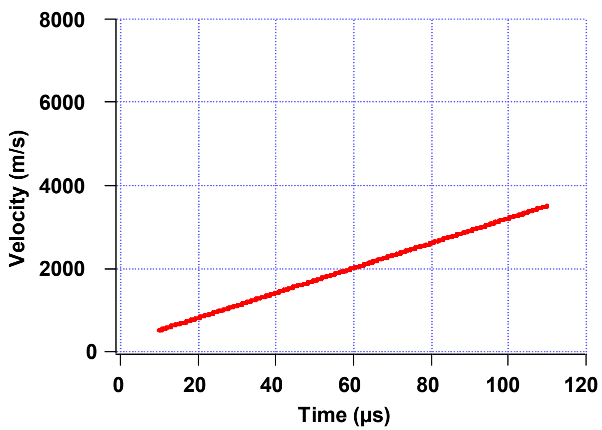
S/N = 1:0



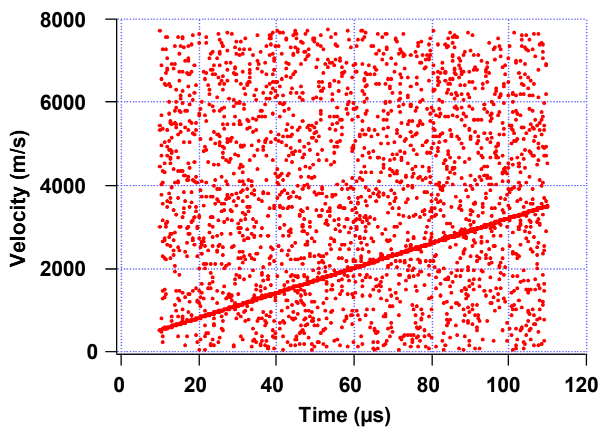
S/N = 1:5



S/N = 1:1

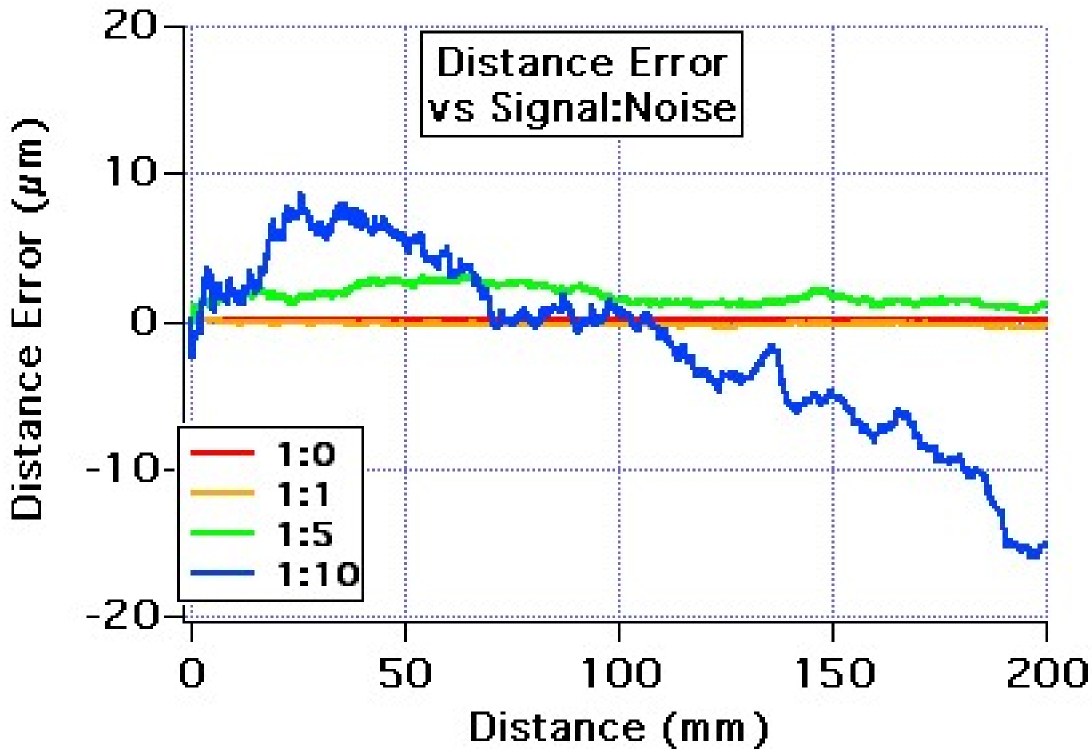


S/N = 1:10



Study the Distance Uncertainty vs Random Noise on the Beat Waveform

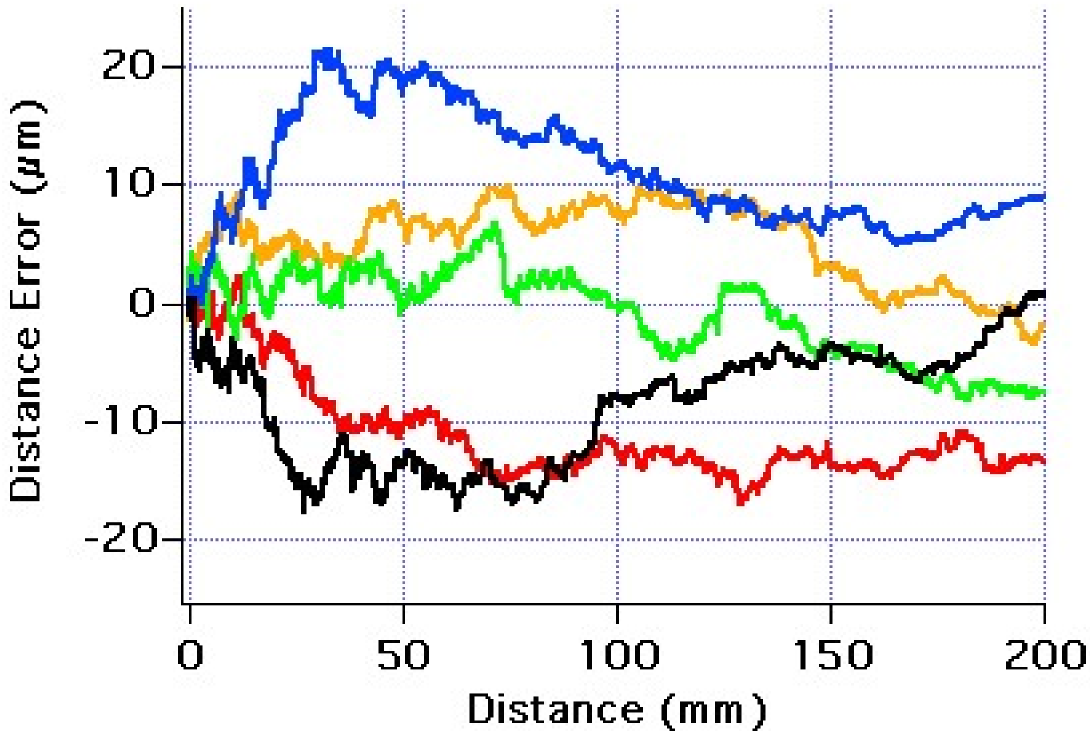
Result: S/N = 1:10 gives < 20 µm error
S/N = 1:1 almost no change in error



S/N = 1:10
might be
a problem--
re-run several
more times

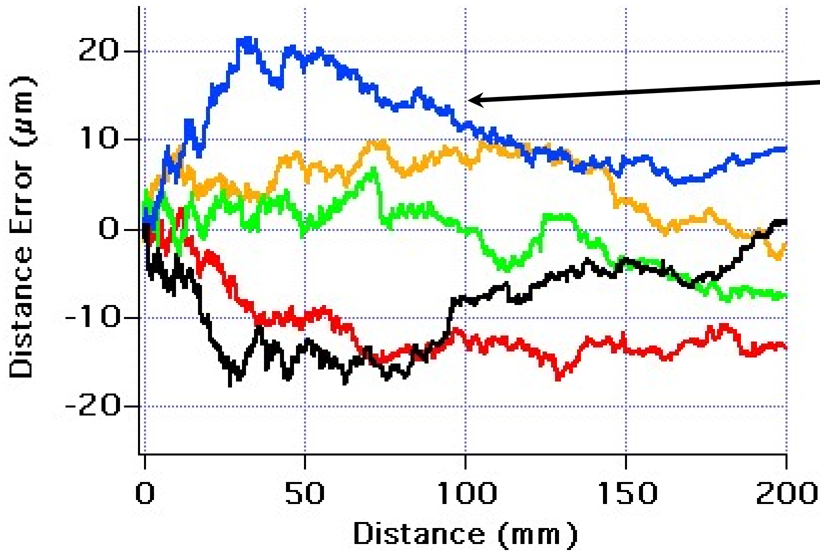
Re-run five more cases with S/N = 1:10

Result: Cannot guarantee < 10 μm uncertainty with S/N = 1:10



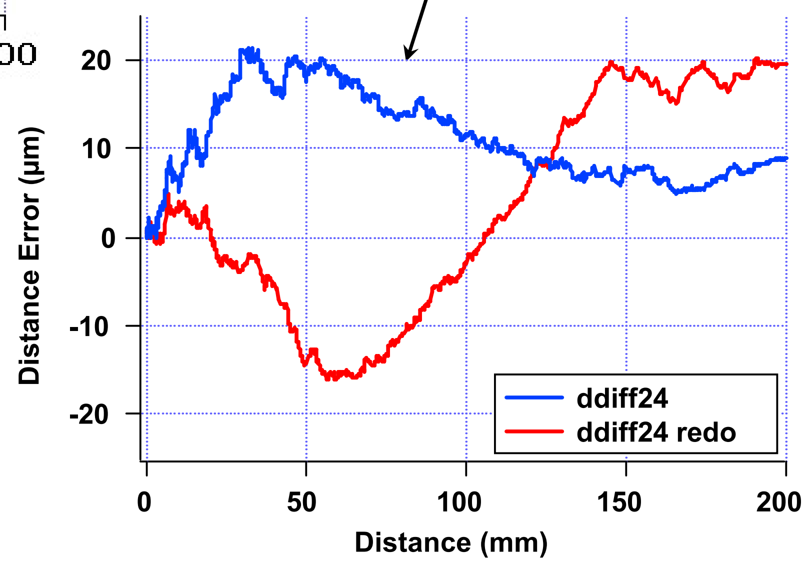
try one
more thing-->

Look more closely at the noise levels in the spectrograms



try tighter polygon extraction on blue curve

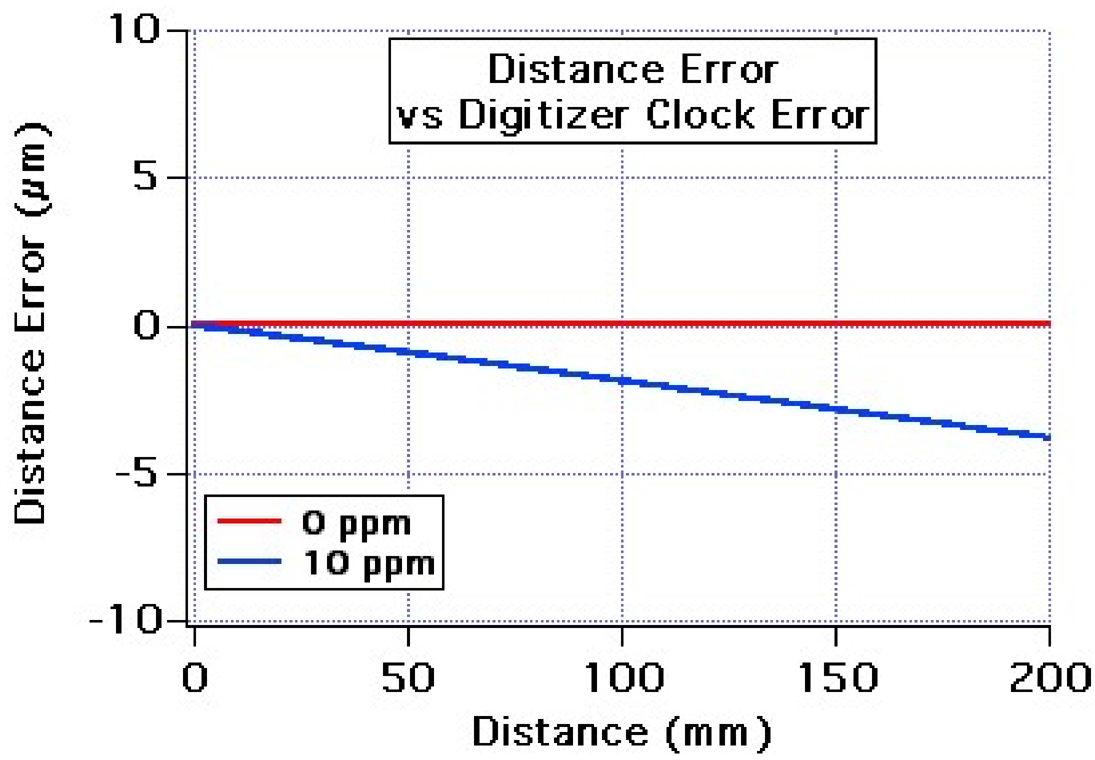
Result is not much better…



Result: cannot guarantee < 10 µm uncertainty with S/N = 1:10

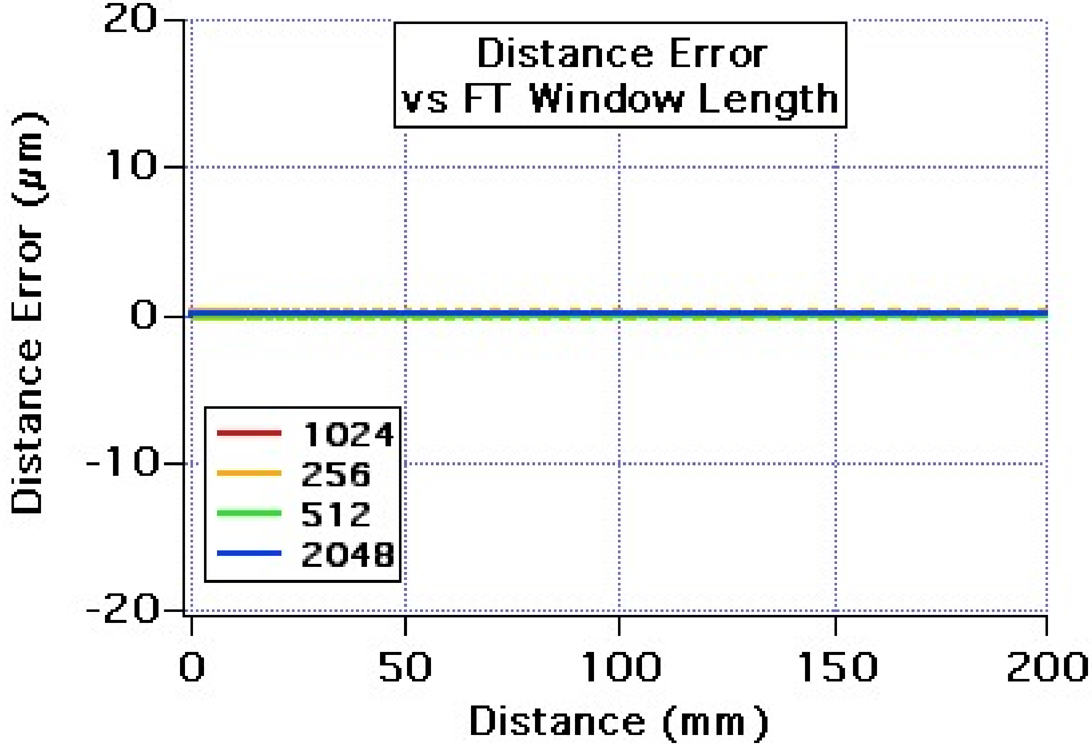
Study the Distance Uncertainty vs Digitizer Clock Error

Result: Effect of 10 ppm error in digitizer sample time
Note: digitizer spec is ±1.5 ppm--very small



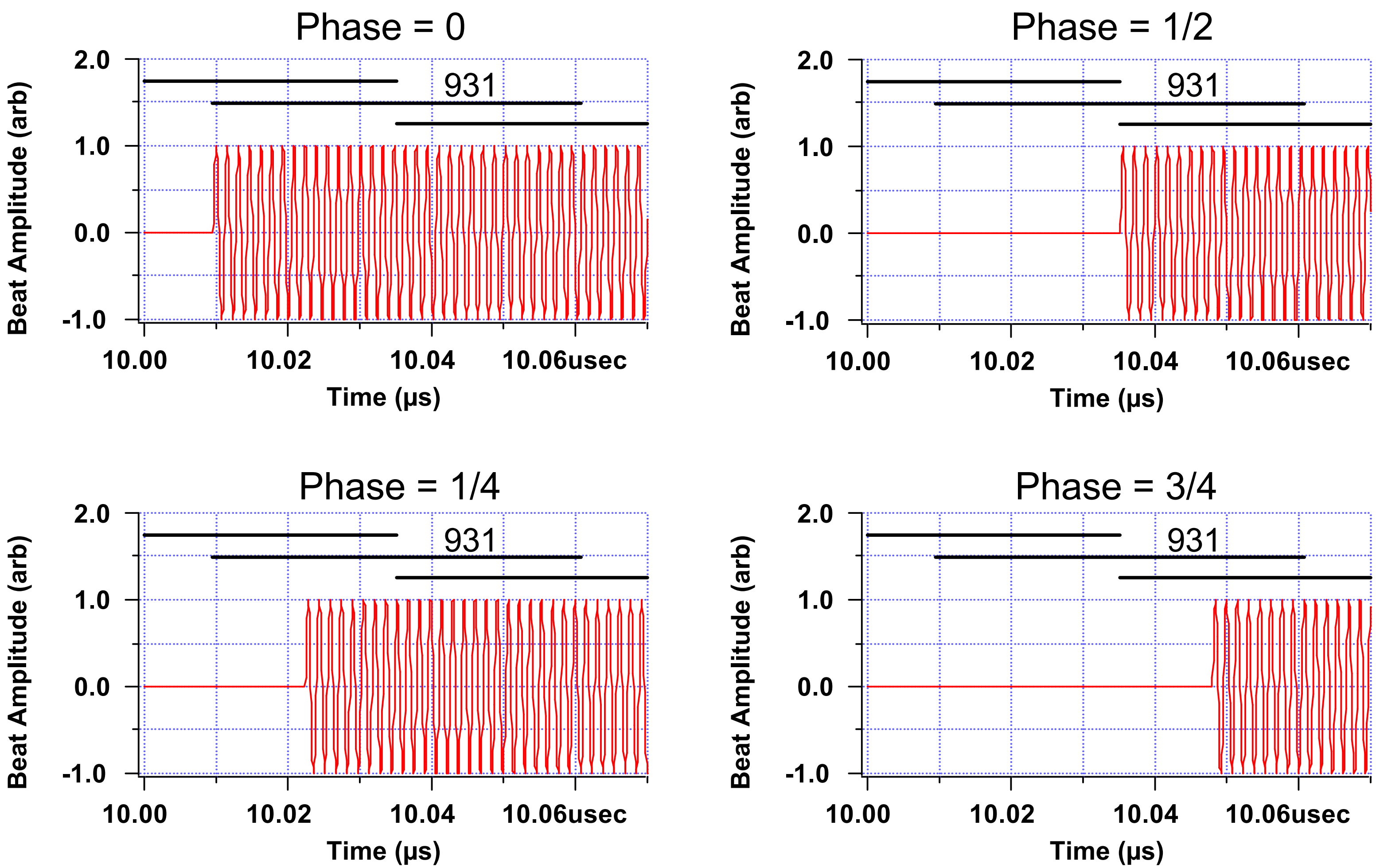
Study the Distance Uncertainty vs FT Window Length

Result: no degradation in error with FT window length

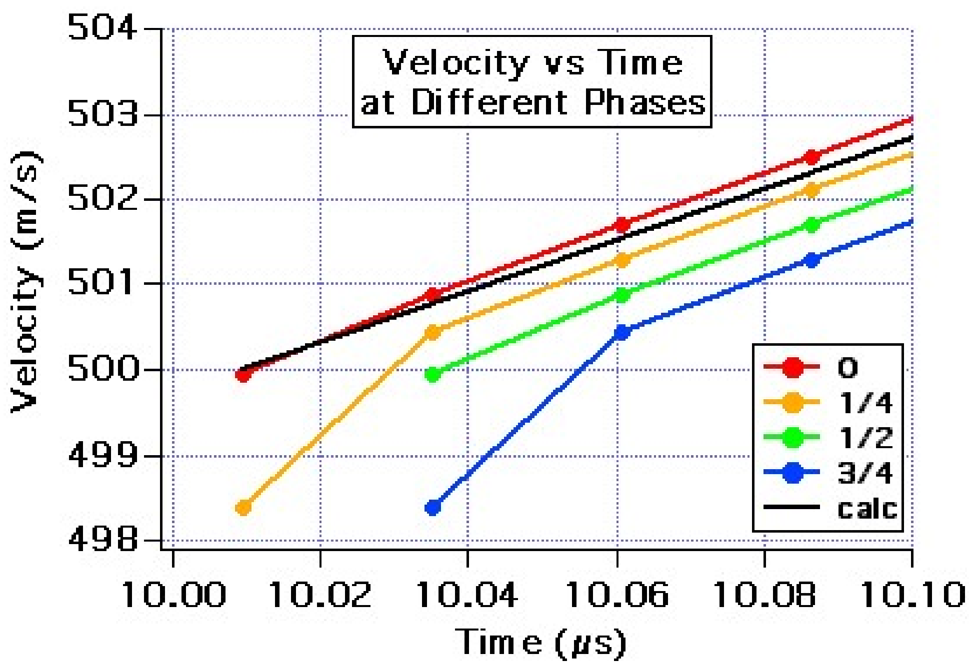


Note: need good S/N to be able to use 256 points = 13 ns FT windows

Study whether there is any effect that depends upon where the signal starts in the FT window



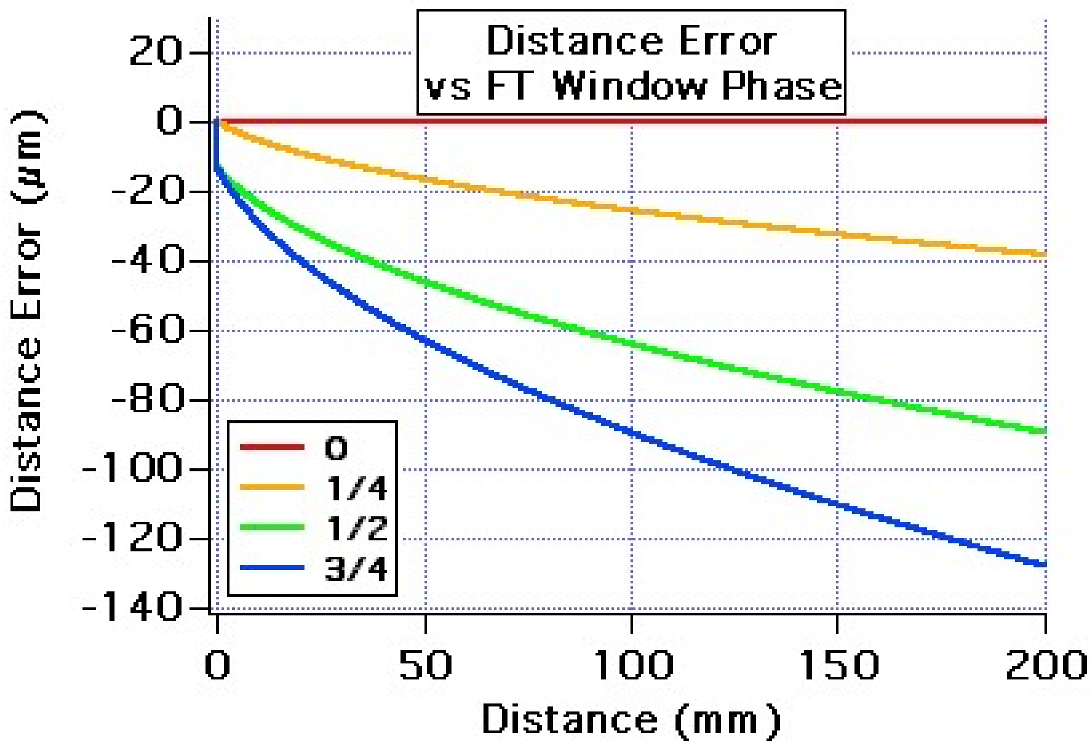
Study whether there is any effect that depends upon where the signal starts in the FT window



1) No data for phase = 1/2 or 3/4.
2) Calculated velocity is low by 1 m/s at phase = 3/4.

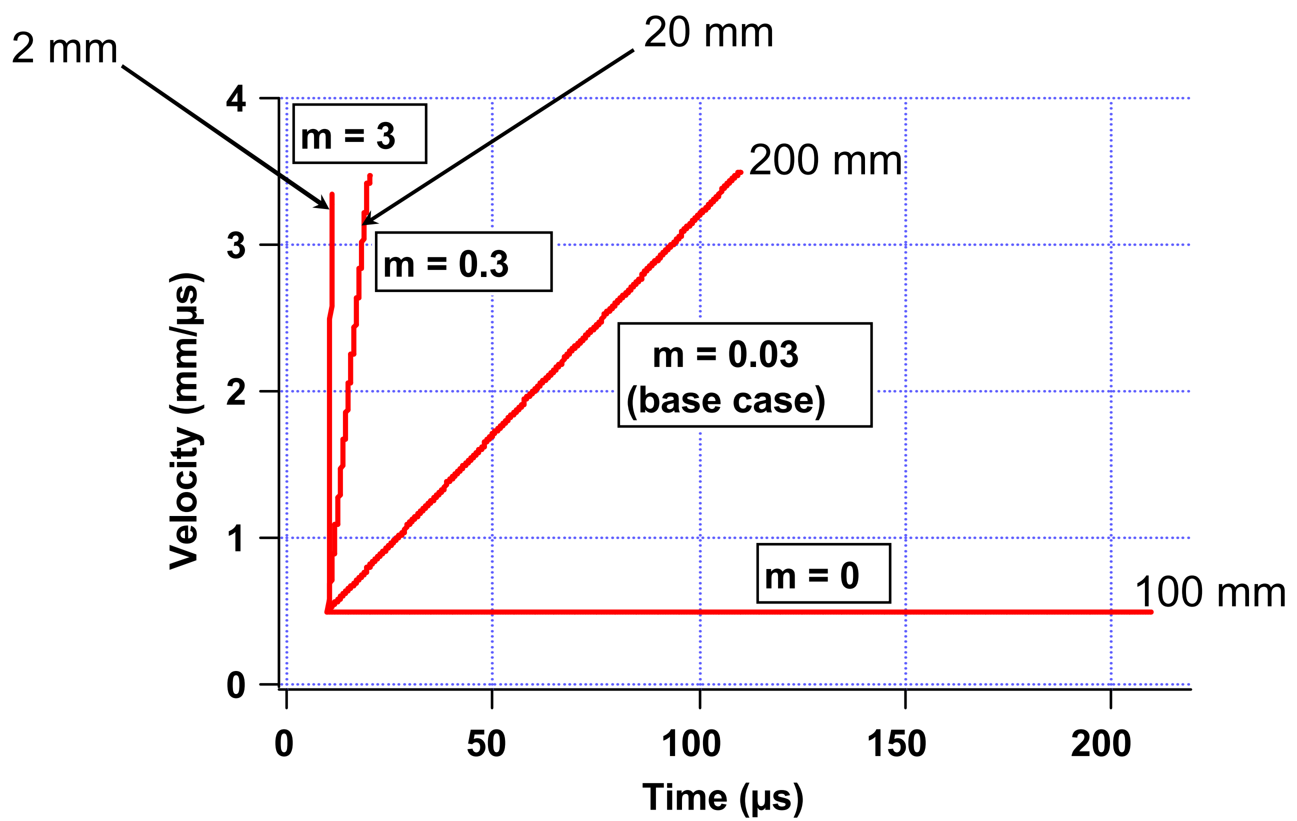
Study the Distance Uncertainty vs Phase

Result: need to make sure the beat waveform starts at the beginning of a Fourier transform window



Study the Distance Uncertainty vs Acceleration

Vary acceleration by factor of 100, plus no acceleration

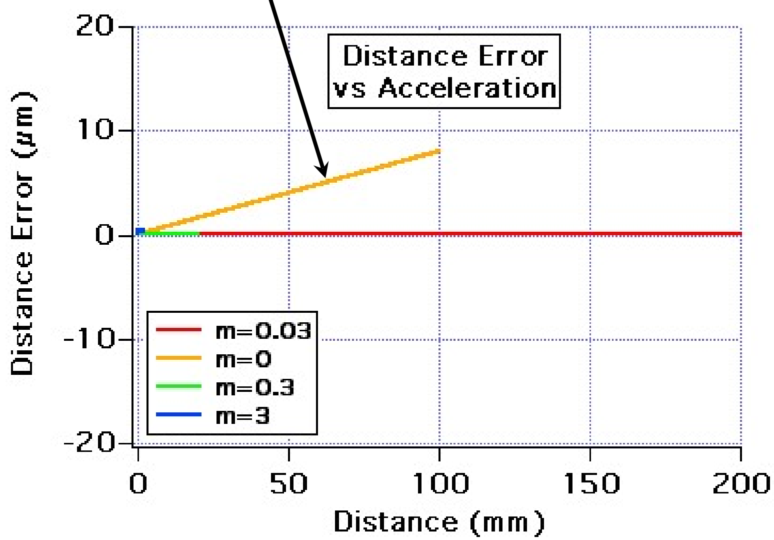


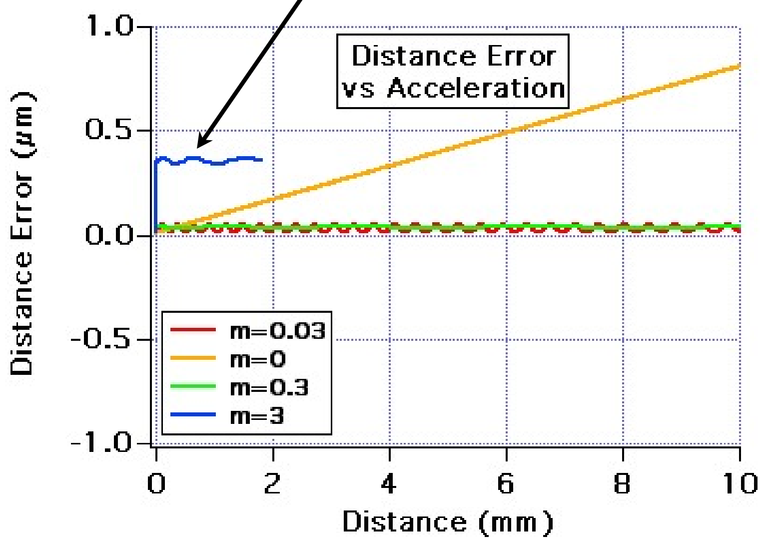
Study the Distance Uncertainty vs Acceleration

Interesting result: no acceleration is worse than acceleration

Note: processed v = 500.04 m/s
--> 0.008% error adds up

1st point v = 525.7 m/s
for m = 3 case





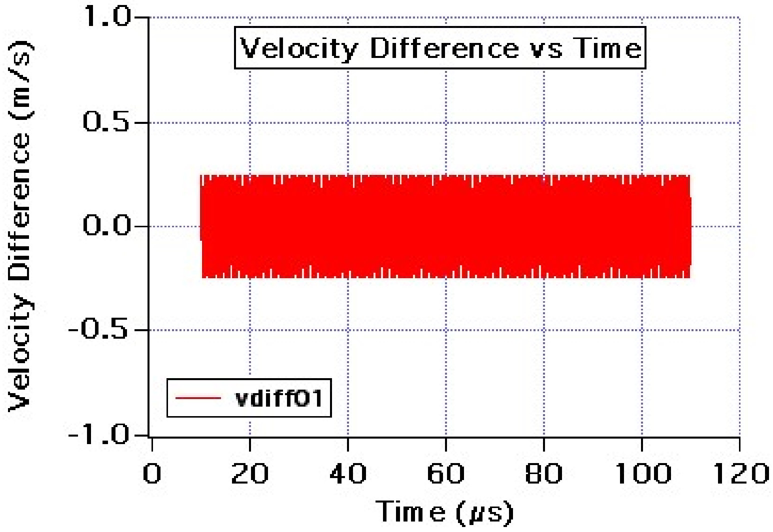
Maybe continue study with accelerations approaching zero.

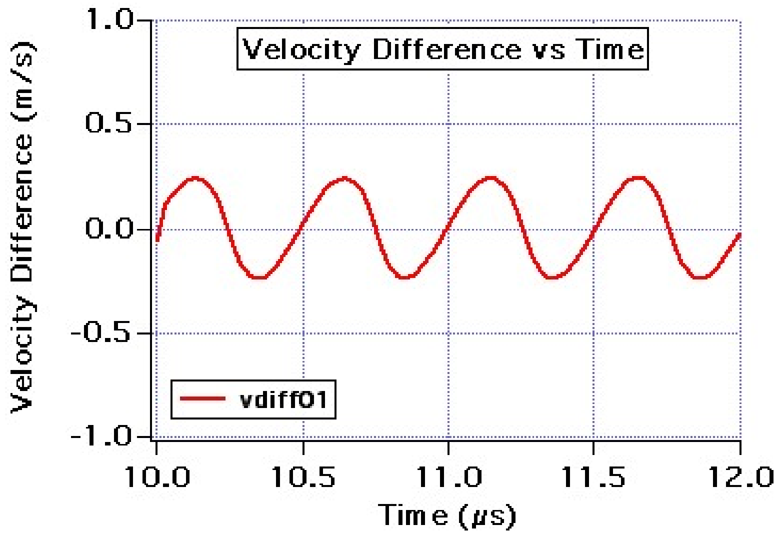
Unexpected result: the code results have oscillatory velocity profiles

The amplitude for the base case is 0.2 m/s,
but does not affect the integral (distance).

This effect is too small to be a concern
for nearly all experiments that I do.

Artifact of MatLab routine?



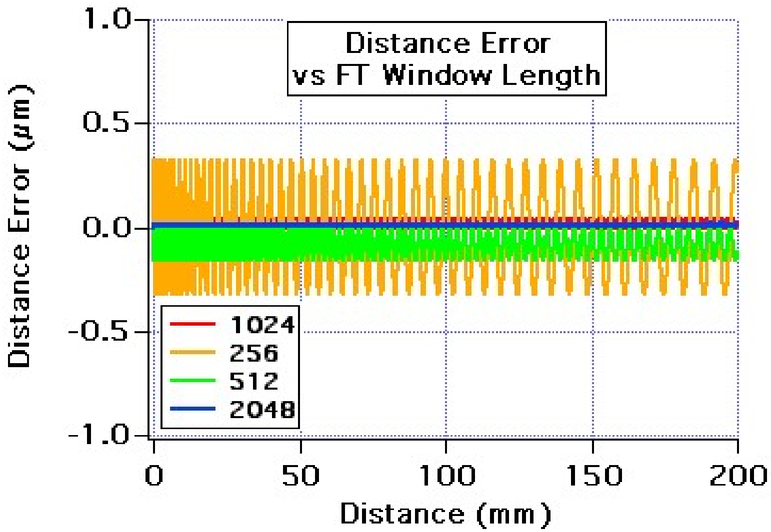


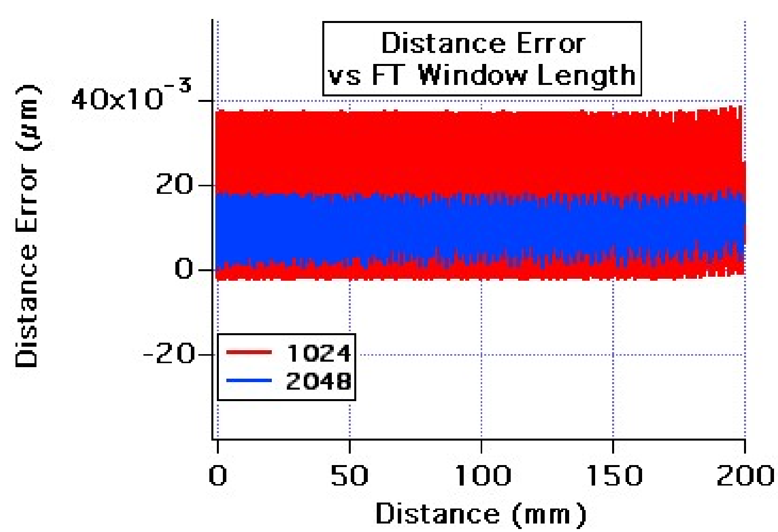
Unexpected result: the code results have oscillatory velocity profiles

Look more closely at the FT window study

FT window	Derror (nm)
256	300
512	50
1024	20
2048	10

The amplitude of the oscillation decreases with increasing FT window length





I have not taken the time to look into this--any ideas?

Summary of distance uncertainties vs various parameters

1. Need < 0.1 nm uncertainty in laser wavelength--not a problem

2. Cannot guarantee < 10 μm uncertainty with S/N = 1:10

3. Digitizer sample rate uncertainty of 1.5 ppm is not a problem

4. FT window length does not impact the distance uncertainty

5. Need to make sure that beat waveform starts at the beginning of a FT window

6. Positive constant acceleration is not a problem, but zero acceleration has small effect

And unexpected result--velocities have very small amplitude oscillations
This does not appear to have an adverse effect on our data analysis